Environment Canada
Conservation and Protection

Environnement Canada
Conservation et protection

National Hydrology Research Institute
Institut national de recherche en hydrologie

Environment CANADA Environnement
2056174k VOL 88 185 T 860200
EXC # 001
GB 707 N42
NHRI CONTRIBUTION
00FF

Inland Waters and Lands Directorate
Saskatoon, Saskatchewan, Canada
Direction générale des eaux intérieures et les terres
Saskatoon, Saskatchewan, Canada

Canada

ISSN 0838-1992

P. Marsh

Surface Water Division
National Hydrology Research Institute
Environment Canada
Saskatoon, Saskatchewan

SOIL INFILTRATION AND SNOW-MELT RUN-OFF IN THE MACKENZIE DELTA, N.W.T.

Paper to be presented at
"5th International Conference on Permafrost"
2-5 August 1988, Trondheim, Norway

NHRI Contribution No. 88007

February 1988

P. Marsh, Research Scientist,
National Hydrology Research Institute

Soil Infiltration and Snow-melt Run-off in the Mackenzie Delta, N.W.T.

SYNOPSIS A field study of snow-melt run-off was carried out in a lake basin in the Mackenzie Delta, N.W.T. The strong negative soil heat flux delayed the arrival of melt water at the snowcover base by refreezing water as ice layers and columns in the snow. Once melt water reached the snowcover base, most infiltrated the soil. However, even though the soil was below 0°C, only a small portion of the melt water which infiltrated the active layer refroze. As a result, the soil warming, due to the release of latent heat of fusion, was not as large as would be expected if all the melt water had refrozen. The large soil infiltration also limits snow-melt run-off, which has important implications to the hydrology of lakes in the Mackenzie Delta.

INTRODUCTION

Run-off from seasonal snowcovers is an important source of water in many alpine and northern environments (Church 1974, Marsh and Woo 1981, Woo et al 1983). Studies of snow-melt run-off in temperate regions have concentrated on warm snowcovers underlain by unfrozen soil (eg. Anderson 1976, U.S. Army 1956, Colbeck 1976), where the influence of the soil is minimal and soil heat flux is small. Under these conditions, snow-melt run-off begins when the irreducible liquid water content of the snowcover is filled, and the snow is warmed to 0°C. This is not the case for snowcovers underlain by soils with temperatures below 0°C.

Until recently, frozen soil was considered to be an impermeable barrier which had little influence on the metamorphism of the overlying snowcover. Recent studies, however, have demonstrated that infiltration into seasonally frozen soils (Kane 1980, Gray et al. 1985, Granger et al. 1984), and soil heat flux may be important (Marsh and Woo 1987). Since the ground in permafrost environments is below 0°C at the beginning of the snow-melt period, soil heat flux removes a significant amount of energy from the snowcover throughout the melt period (Marsh and Woo 1984, 1987). This increases the freezing of melt water into ice layers and ice columns in the snow, ensures that much of the soil infiltration freezes, and may result in the formation of basal ice. As a result of these processes, it is necessary to consider the combined snow-soil system in order to predict the initiation and volume of snow-melt run-off. In permafrost regions, snow-melt run-off may not occur until after the liquid and thermal capacity of the snow and soil are filled (Marsh and Woo 1984).

The purpose of this paper is to demonstrate the importance of the cold, underlying soil in delaying and limiting snow-melt run-off in permafrost environments.

STUDY AREA AND METHODOLOGY

Field work was carried out at a small (0.069 km^2) lake (unofficial name NRC Lake) approximately 5 km southwest of Inuvik (Marsh 1986). NRC Lake is perched above the surrounding Mackenzie River distributary channels. The basin surrounding this lake is 0.43 km^2 in area, and is covered by an open, mature spruce forest. The zone beneath the lake is unfrozen, while the permafrost is in excess of 80 m in thickness beneath the land areas surrounding the lake (Johnston and Brown 1964), and the active layer is up to 0.5 m deep by late summer. The soils are silts with an organic content of between 15 and 30%.

In the Inuvik area, mean annual precipitation is 266 mm, of which 57% occurs as snow. Snow-melt is initiated in mid May when air temperatures rise above 0°C. Spring flood water from the Mackenzie River is the primary source of water for NRC Lake. Higher-elevation delta lakes which do not flood annually experience declining water levels between flooding events (Marsh 1986).

Daily changes in the soil moisture profile were determined at 3 sites at NRC Lake using a twin probe gamma density meter. Individual measurements at 5 cm increments are accurate to $\pm$2 mm of water. In addition, snow and soil temperatures were measured at each of these sites. Snow depth and density measurements were taken to determine mean snowcover water equivalent, and changes in snowcover properties were monitored daily at two snow-pits using the method described by Marsh and Woo (1987). Measurement of NRC Lake stage provided estimates of melt run-off from the surrounding basin.

Micrometeorological measurements were made at a height of 1 m above the snow surface. A Campbell CR21 data

logger recorded air temperature, relative humidity, wind, net radiation, and precipitation. Hourly averages of these parameters were obtained from measurements taken at 60-second intervals. Surface snow-melt was calculated using the bulk transfer approach (Price and Dunne 1976, Heron and Woo 1978, Moore 1983).

SNOW-MELT RUN-OFF

The snow-melt period may be divided into two well-defined intervals. The first begins at the start of melt and continues until the entire snowcover has been warmed to 0°C, and has been wetted (Figure 1). The second continues until the snowcover has been depleted. It is during this second period when snow-melt run-off may occur. In 1986, the initial warming and wetting of the snow-pack covered the period May 28 to May 31, and the snowcover was depleted by June 4. The remainder of this paper will deal primarily with the 1987 melt season, when the two periods were May 22 to 26 and 27 to 31 respectively.

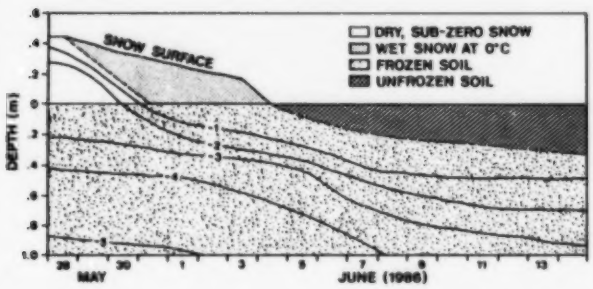

Figure 1. Changes in snow and soil temperatures during the snow-melt period in 1986. Note that the melt period can be divided into two intervals, the first from May 28 to May 31 when the snowcover is warming to 0°C and is being wetted, and the second continuing to June 4 when the snowcover is depleted.

Initial metamorphism of the snow cover

During this phase of the snow-melt period, warming of the snow and soil plays an important role in delaying the arrival of melt water at the snow base. Between May 22 and May 26 conduction through the isothermal surface snow layer (Figure 2) was negligible, and therefore the only source of energy available to warm the snowcover was from the release of latent heat of fusion due to the freezing of water as ice layers and ice columns within the snowcover. The freezing of 3 mm of water supplied the 0.9 MJ/m^2 of energy that was required to warm the snowcover to 0°C (Figure 2 and Table 1).

Of much greater importance in delaying the snow metamorphism between May 22 and May 26, however, was the large soil heat flux. Calculation of the change in heat storage in the top metre of the soil (Figure 2), and the heat conduction below 1 m, show that there was a soil heat flux of 7.2 MJ/m^2 (Table 1) during this period. This soil heat flux was driven by the freezing of 21 mm of water within the snowcover and the conduction downward into the soil of the released latent heat.

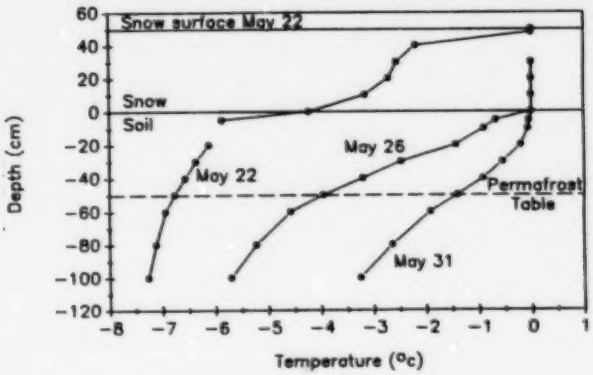

Figure 2. Snow and soil temperatures at the start of snow-melt (May 22), when melt-water first reached the snow pack base (May 26), and at the end of snow-melt (May 31) in 1987.

Date	Snow-melt		Snow cold content		Soil heat flux		Snow liquid water storage	Total
	MJ/m^2	mm	MJ/m^2	mm	MJ/m^2	mm	mm	mm
22-26 May	15.0	45	0.9	3	7.2	21	26	50
27-31 May	26.3	79	0	0	7.7	23	0	23
TOTAL	41.3	124	0.9	3	14.9	44	26	73

Table I. Surface snow-melt, and the energy required to account for the observed warming of the snow and soil in 1987.

In addition to the 24 mm of water which froze within the snowcover, an additional 26 mm of melt water filled liquid storages in the snow-pack. The combination of refreezing and filling of liquid storages delayed the arrival of melt water to the snowpack base by 4 days. Approximately half of this delay was due to the soil heat flux alone.

Soil infiltration

Once melt water reaches the snow-pack base, it may either run off laterally or infiltrate the soil. Field observations in both 1986 and 1987 suggest that the majority of the melt water at the Mackenzie Delta study sites infiltrates into the soil and there is a minimal amount of surface run-off. For example, liquid water was not observed draining from any late lying snow patches, and ponded surface water occurred only in a few larger depressions. A small rill draining into

NRC lake had no surface flow in 1986 and only a small volume of flow in 1987. In addition, no basal ice was observed in 1986 and only small isolated patches in 1987. These observations suggest that the infiltration capacity of the soils was not exceeded in 1986 and was exceeded only in a few locations in 1987. The mean infiltration capacity of these frozen soils is probably between the mean pre-melt snow-pack water equivalent of 51 mm in 1986 and 139 mm in 1987. The gamma soil density measurements, which were carried out in 1987, substantiate these visual observations. At each measurement location, water infiltrated throughout the total thickness of the active layer (Figure 3) and total infiltration was 52, 61, and 111 mm with a mean value of 75 mm. At the gamma measurement sites, the mean premelt snow water equivalent in 1987 was 92 mm. However, surface energy balance calculations indicate a total sublimation of 8 mm. Therefore, only 84 mm of water was available for infiltration. Considering the errors involved with measuring soil water storage for a profile 40 cm in thickness, the measured mean soil infiltration of 75 $\pm$ 16 mm is essentially equal to the available snow water equivalent of 84 mm. Since the soil was always below 0°C during this period (Figure 2), little of the water was available for run-off to the lake. This is supported by the small volume of visible run-off to the lake and by the nearly constant lake level over the melt period.

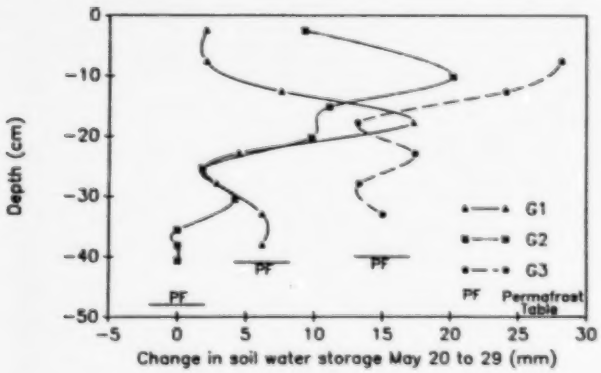

Figure 3. Changes in soil moisture between May 20 and May 29, 1987.

The soil infiltration also played an important role in the warming of the active layer and underlying permafrost during the May 26 to 31 period. Since the snowcover was isothermal at 0°C during this period (Figure 2), heat conduction downward from the snow surface to the underlying soil was impossible. The only source of energy was the movement of water downward into the soil, and its resultant refreezing and release of latent heat. Since the water infiltrated deeply into the soil (Figure 3), it provided an efficient mechanism for energy transfer. However, the change in soil heat storage indicates that not all the infiltrated water refroze. The calculated change in heat storage of 7.7 MJ/m^2 (Table 1) required the freezing of only 23 mm of water within the soil. The remainder of the infiltrating water (52 mm of the 75 mm which infiltrated the soil) did not freeze. As shown by other studies (eg. Scott 1969, Akimov et al. 1984), silts with a temperature between 0 and -2°C contain unfrozen water of between 5 and 30% by dry soil weight. Assuming that 10% by dry soil weight of the infiltrated water at the study sites did not freeze, this would represent approximately 20 mm of unfrozen water in the 40 cm thick frozen active layer. As Tice et al. (1978) suggested, this may be a lower limit. In fact a higher percentage of unfrozen water may occur with increasing ice content in the soil.

DISCUSSION AND CONCLUSIONS

These results have general implications for snow-melt run-off and active layer warming, and specific implications to the hydrology of lakes in the Mackenzie Delta. First, the cold substrate is responsible for removing considerable energy from the snow-pack during the melt period. The primary effect is to extend the snow-melt period. Second, soil infiltration may consume a large proportion of the initial snowcover water equivalent and therefore limit direct snow-melt run-off. The freezing of this infiltration is an important source of heat which can warm the active layer prior to the removal of the snowcover. However, in fine-grained soils, a significant portion of this infiltrating water may not refreeze, even if the soil is below 0°C. This effectively limits the energy available to warm the active layer, and must be taken into account when modelling active layer warming and the increase in the thaw depth once the snowcover is removed.

Lakes which are perched at a sufficiently high elevation, do not receive flood water from the Mackenzie River at annual intervals. As a result, they are dependent on run-off from the surrounding basin to sustain water levels between flooding events. However, snowmelt run-off to these lakes in negligible and Marsh (1986) found that summer run-off is also near zero. In addition, Marsh and Bigras (1988) showed that summer evaporation (230 mm) from the lakes is greater than summer precipitation (101 mm) onto the lake surface. As a result, these high perched lakes experience a negative water balance and declining water levels between flooding events (Marsh 1986). These lakes are therefore very sensitive to reduced spring flood levels due to flow regulation. Flow regulation could result in decreased flood frequency and declining lake levels for high sill elevation lakes. The number of lakes and the total lake area would decline with serious consequences to the ecology of the Mackenzie Delta.

ACKNOWLEDGEMENTS

The generous logistical support of The Polar Continental Shelf Project, Department of Energy, Mines, and Resources, and the Inuvik Scientific Resource Centre, Department of Indian and Northern Affairs is gratefully acknowledged. I would like to thank M. Ferguson for her assistance in the field.

REFERENCES

Akimov, Y.P., E.D. Yershov, and V.G. Cheveryov. 1984. The physicochemical nature of the formation of unfrozen water in frozen soils. Permafrost, Fourth International Conference, Final Proceedings. Fairbanks, Alaska, 195-199.

Anderson, E.A. 1976. A point energy and mass balance model of a snowcover. N.O.A.A. Tech. Report NWS 19, 150 pp.

Church, M. 1974. Hydrology and permafrost with reference to northern North America. Proc. Workshop Seminar on Permafrost Hydrology, Can. Nat. Comm., IHD, Ottawa, 7-20.

Colbeck, S.C. 1976. An analysis of water flow in dry snow. Water Resour. Res., 12, 523-527.

Granger, R.J., D.M. Gray, and G.E. Dyck. 1984. Snowmelt infiltration to frozen prairie soils. Can. J. Earth Sci., 21, 669-677.

Gray, D.M., P.G. Landine, and R.J. Granger. 1985. Simulating infiltration into frozen prairie soils in streamflow models. Can. J. Earth Sci., 22, 464-472.

Heron, R. and M.K. Woo. 1978. Snow-melt computations for a high arctic site. Proc. 35th Eastern Snow Conf., 162-172.

Johnston, G.H. and R.J.E. Brown. 1964. Some observations on permafrost distribution at a lake in the Mackenzie Delta, N.W.T., Canada. Arctic, 17, 163-175.

Kane, D.L. 1980. Snowmelt infiltration into seasonally frozen soils. Cold Regions Sci. Technol., 3, 153-161.

Marsh, P. and S. Bigras. 1988. Evaporation from Mackenzie Delta Lakes, N.W.T., Canada. Arctic and Alpine Res., 20(2). In press.

Marsh, P. and M.K. Woo. 1981. Snowmelt, glacier melt, and high arctic streamflow regimes. Can. J. Earth Sci., 18, 1380-1384.

Marsh, P. and M.K. Woo. 1984. Wetting front advance and freezing of meltwater within a snow cover 1. Observations in the Canadian Arctic. Water Resour. Res., 20, 1853-1864.

Marsh, P. and M.K. Woo. 1987. Soil heat flux, wetting front advance and ice layer growth in cold, dry snow covers. Snow Property Measurement Workshop, Lake Louise, Alta., April 1-3, 1985, NRC Technical Memorandum 140, 497-524.

Marsh, P. 1986. Modelling water levels for a lake in the Mackenzie Delta. Cold Regions Hydrology Symposium, American Water Resources Association, Fairbanks, Alaska, 23-29.

Marsh, P. 1988. Hydrology of Mackenzie Delta Lakes. Northern Rivers and Lakes Workshop, Knowing the North: Integrating Tradition, Technology and Science. Boreal Institute for Northern Studies, University of Alberta, in press.

Moore, R.D. 1983. On the use of bulk aerodynamic formulae over melting snow. Nordic Hydrology, 14, 193-206.

Price, A.J. and T. Dunne. 1976. Energy balance computations on snowmelt in a subarctic area. Water Resour. Res., 12, 686-694.

Scott, R.F. 1969. The freezing process and mechanics of frozen ground. U.S. Army, Cold Regions Research and Engineering Laboratory, Monograph II-D1, 65 pp.

Tice, A.R., C.M. Burrous, and D.M. Anderson. 1978. Determination of unfrozen water in frozen soil by pulsed nuclear magnetic resonance. Third International Conference on Permafrost, Edmonton, Canada, 150-155.

Woo, M.K., P. Marsh, and P. Steer. 1983. Basin water balance in a continuous permafrost environment. Proc. Fourth International Conference on Permafrost, Fairbanks, Alaska, 1407-1411.

U.S. Army. 1956. Snow hydrology, Summary report of the snow investigations, Corps of Enging., North Pac. Div., Portland, Oreg., 437 pp.